Heavy Flavour
Production at the
Tevatron
Theory hits Reality in Tevatron Run I

Measured and predicted b production cross section as function of pt at CDF and DØ (B+, and incl b respectively). Measurement > theory.

Since then: better theory (e.g. FONLL). And a better experiment: Tevatron RunII, upgraded collider and detectors

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Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.
Tevatron Run II

- Run II started in 2001
- Tevatron collides protons and anti-protons at cm energy 1.96 TeV
- 2.5 M times per second.
- Huge b and charm x-section.
- Detector upgrades for heavy flavour physics, e.g. high-resolution Si vtx trackers, trigger upgrades.
Tevatron Luminosity

- 3/fb delivered
- ca 1/fb of those analysed
- (all numbers per experiment)

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Detectors

- Both detectors good for heavy flavour physics, with excellent vtx resolution, muon coverage, trigger...
- DØ’s special skill: Large muon coverage, to $|\eta| \leq 2$. Excellent for leptonic and semileptonic modes.
- CDF’s special skill: High bandwidth displaced-track trigger. Unique capabilities in fully hadronic modes.
Tevatron Events

• One (usually very busy) event every 396 ns
• Write to tape only \( \sim 0.003\% \) (CDF).
• Which ones? Trigger crucial.
• Two strategies for heavy flavour: Leptons, or displaced tracks.

CDF at Tevatron
• CDF’s Displaced Track Trigger ⇒ finds B’s
• New Si microstrip detector → excellent time resolution.
p − \( \bar{p} \) collisions every 396 ns
View live events at
http://www.fnal.gov/pub/now/live events/cotview.html
yor here)
Di-μ trigger

- Finds $J/\psi$, $B \to J/\psi X$, $B \to \mu\mu(X)$
- Very clean trigger in hadron environment.
- Especially powerful at DØ with its excellent $\mu$ coverage.

180,000 $J/\psi \to \mu\mu$ in 0.11/fb
28,000 $B \to J/\psi K$ in 1.6/fb at DØ
Displaced Track Trigger

- Requires two tracks with $pt > 2\text{GeV}$ $IP > \sim 0.1\text{mm}$
- Finds fully hadronic $B$ and $D$ decays (the majority)
- Designed for $B$, but also good for Charm. E.g. in $1.1/\text{fb}$ at CDF: $13 M D^0 \rightarrow K\pi$, $0.3M D_s \rightarrow \Phi(KK)\pi$.
- CDF’s two-track trigger has enough bandwidth to run w/o additional lepton requirements.

Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.
Track + lepton

- A mixture between the above
- Requires (at least) one displaced track, and one lepton (e or $\mu$).
- Finds $B \rightarrow D\ell\nu$

D mass in $B \rightarrow D(K_sX)\ell\nu$

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Direct Charm Meson production x-section

- Fully reconstructed D meson, hadronic modes from 5.8/pb.
- Plot shows $\sigma(|y| \leq 1)$ for $D^\circ$. Grey band shows FONLL prediction. Plots for $D^*$, $D^+$, $D_s$ look similar.
- Measured/FONLL $\sim$1.5–2, but OK within uncertainties.

\[
\sigma(D^0, p_T > 5.5\text{GeV}, |y| \leq 1) = (13.3 \pm 0.2(\text{stat}) \pm 1.5(\text{sys})) \mu\text{b}
\]

Use impact parameters to distinguish direct charm from $B$
B x-section

- Inclusive $B \rightarrow J/\psi X$, $B \rightarrow D\ell\nu X$ [not in this plot] and excl $B^+ \rightarrow J/\psi K^+$ agree well with each other, Run I, and FONLL.

- Latest result: exclusive $B^+ \rightarrow J/\psi K^+$

$$\sigma(p\bar{p} \rightarrow B^+, p_t > 6\text{GeV}, |y| < 1) = (2.64 \pm 0.12(\text{stat}) \pm 0.21(\text{sys})) \mu\text{b}$$

8.2±0.2k

$B^+/− \rightarrow J/ψK^+/−$
in 0.74/fb

CDF II Preliminary 740 pb⁻¹

CDF preliminary 0.74/fb

more numbers in backup slides

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correlated $b\bar{b}$ x-section

- For correlated $b\bar{b}$ x-section (both $b$ quarks within a certain, central rapidity and pt range), higher order terms expected to be smaller, NLO should work better.
- Past Tevatron results inconclusive/contradictory.
- Table shows ratio of previously measured $\sigma$/NLO-prediction. (New result on next slides.)

Note: Table 2: Ratio $R_{2b}$ of $\sigma_{bb}$, the observed cross section for producing both $b$ and $\bar{b}$ quarks, centrally and above a given $p_T^{\text{min}}$ threshold, to the exact NLO prediction.

Fabio Happacher showed this table at DIS-06 (http://www-conf.kek.jp/dis06/doc/WG5/hfl20-happacher.ps)

[I modified they ways the uncertainties are presented, possibly adding mistakes and rounding errors in the process]
Correlated $b\bar{b}$ and $c\bar{c}$ x-section using $\mu\mu$

- **Reconstruct $\mu\mu$ pairs**
  
  - $p_T \geq 3 \text{GeV}$
  - $|\eta| \leq 0.7$
  - $m_{\mu\mu} \in [5, 80] \text{GeV}$

- **Corresponds to $b\bar{b}$ pairs**
  
  - $p_T \geq 2 \text{GeV}$
  - $|y| \leq 1.3$

CDF preliminary, 0.74/fb

Events/(GeV/c$^2$) of events selected for this study

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Correlated $b\bar{b}$ and $c\bar{c}$ x-section using $\mu\mu$

- Use impact parameters to distinguish
  - $b \rightarrow \mu$, $b \rightarrow \mu$
  - $b \rightarrow \mu$, $c \rightarrow \mu$
  - $c \rightarrow \mu$, $c \rightarrow \mu$
  and contributions with one or more prompt $\mu$.

Fit done in 2-D. This is the 1-D projection of 2-D IP distribution and fit.
Correlated $b\bar{b}$ and $c\bar{c}$ x-section: results

- **x-sections:**
  \[
  \sigma_{b \rightarrow \mu, \bar{b} \rightarrow \mu} = (1549 \pm 133) \text{pb} \quad \sigma_{c \rightarrow \mu, \bar{c} \rightarrow \mu} = (624 \pm 104) \text{pb}
  \]
  \[
  \sigma_{b\bar{b}} \left( p_T \geq 6 \text{GeV}, |y| \leq 1 \right) = (1618 \pm 148 \pm \left[ \sim 400 \text{ fragmentation} \right]) \text{nb}
  \]

- **Ratios (includes both exp. and theory error):**

  \[
  \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}}_{b \rightarrow \mu, \bar{b} \rightarrow \mu} = 1.2 \pm 0.2 \quad \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}}_{c \rightarrow \mu, \bar{c} \rightarrow \mu} = 2.7 \pm 0.6
  \]

  With Peterson fragmentation parameter:

  \[
  \epsilon = 0.006 \quad \epsilon = 0.002^* \]

  \[
  \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}}_{b \rightarrow \mu, \bar{b} \rightarrow \mu} = 1.0 \pm 0.2 \quad \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}}_{c \rightarrow \mu, \bar{c} \rightarrow \mu} = 1.6 \pm 0.4
  \]


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Charm pair x-section
kinematic separation of production mechanisms

Flavour Creation
large $\Delta \varphi$

Flavour Excitation
large(ish) $\Delta \eta$

Gluon Splitting
small $\Delta \varphi$

Otto Hinzweber, University of Bristol on behalf of CDF and DØ.
Charm pair x-section

- Collinear production as important as back-to-back.
- Pythia (tune A, LO + parton shower): Overall OK but under-estimates collinear, and over-estimates back-to-back production.
- Similar for D+D*

CDF Run II Preliminary, 1.1 fb⁻¹

D⁰ D* x-section vs ΔΦ

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Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.
Charmonium/Bottomium

- Can’t produce colour-neutral $J^P = 1^-$ pair by simple gluon fusion.
- Simplest solution: produce a coloured state and “bleach” by radiating off one (hard) gluon.
- Dramatically fails to predict $x$-sections (meas/predict $\sim 30$ for $J/\psi$).


CHARM 07, Ithaca NY, 05 Aug 2007 Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.
Charmonium/Bottomium

NRQCD - Colour Octet

- colour radiated off by soft gluons.
- Adjustable hadronisation parameters allow match to observed p_t spectra and x-sections.
- Predicts transverse polarisation of J/ψ

pQCD

- Include 2nd order diagrams of the type shown above.
- LO pQCD calculation matches observed p_t spectra and x-section.
- Predicts longitudinal polarisation of J/ψ, increasing with pt.

E.L. Berger, J. Qiu, Y. Wang hep-ph/0411026

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Jonas Rademacker (University of Bristol) on behalf of CDF and DØ.
Charmonium/Bottomium

NRQCD - Colour Octet

QCD with higher order terms

Both models describe differential x-sections well (data from RunI)
But they predict different polarisations - see next slide


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Measuring onium polarisation

- Measure
  \[ \alpha = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} \]

- \( \alpha = 0 \) if all helicity states equally likely.

- Extract from angular distribution. \( \theta^* \) is the angle between \( J/\psi \) and \( \mu \) in \( J/\psi \) restframe.

\[ \frac{dN}{d(\cos \theta^*)} \propto 1 + \alpha \cos^2 \theta^* \]

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J/ψ polarisation

- Select ca 0.8M prompt J/ψ in 0.8/fb (B→J/ψX removed by IP-significance cuts)

- Fit $\cos \theta^*$ distribution in bins of pt - below are 3 examples:

  - 4-6GeV
  - 9-12GeV
  - 17-30GeV

Yield: 783,600
J/ψ polarisation

- Significant longitudinal polarisation, in contradiction to NRQCD/colour octet prediction.

CDF II Preliminary, 800 pb⁻¹

$\alpha_{\text{prompt}}$: Prompt J/ψ Polarization

Zero polarization
Theoretically cleaner because no feed-down from higher states

Also observe significant longitudinal polarization
\[ \Upsilon(1S), \Upsilon(2S) \) polarisation

- DØ find 420,000 \( \Upsilon(nS) \).
- Single-trigger selection reduces this to 170,000 \( \Upsilon(nS) \) from di-\( \mu \) trigger.

\[ \chi^2/\text{ndf} \ 110.2 / 118 \]

2 Gaussian fit
\( \Upsilon(1S) \) polarisation

- Find significant, \( p_T \) dependent longitudinal polarisation.
- Incompatible with NRQCD/colour-octet

\begin{itemize}
  \item \text{kt-factorisation} \quad \text{[Baranov, hep-ph/0707.0253]}
  \item \text{NRQCD} \quad \text{Braaten, Lee, Phys. Rev. D63, 071501 (R) (2001)}
\end{itemize}

DØ, Run 2 Preliminary, 1.3 fb\(^{-1}\)

DØ measurement \(|y| < 2\)

prev CDF result with \(|y| < 0.4\)


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$\Upsilon(2S)$ polarisation

- Same study for $\Upsilon(2S)$
- Not incompatible with NRQCD/colour-octet within (lower) stats.

DØ, Run 2 Preliminary, 1.3 fb$^{-1}$
Measuring $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.

- Experimentally tricky because of soft $\gamma$ in $\chi_{cJ} \rightarrow J/\psi \gamma$. Soft photons give bad energy resolution.

- Good lumi at Tevatron allows use of conversion $\gamma \rightarrow e^+ e^-$. It’s inefficient, but has good energy resolution.
Measuring $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})}$.

- Excellent mass resolution.
- Separate prompt from B using decay distance
- Find:
  
  $$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.70 \pm 0.04(\text{stat}) \pm 0.03(\text{sys}) \pm 0.06(\text{BF})$$

  for $p_t(\chi_{cJ}) \in [4, 20] \text{GeV}$
- Colour octet predicts 5/3 (counting of spin states).

\[ \sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.70 \pm 0.04 \text{(stat)} \pm 0.03 \text{(sys)} \pm 0.06 \text{(BF)} \]
Conclusions

- Plenty of heavy flavour produced at Tevatron. Triggers originally designed for beauty find loads of that - and charm.
- Active field at Tevatron, most results shown < 1y old.
- Keep challenging theory with measurements beyond ‘just $d\sigma/dp$’: angular correlations, polarisation, .... first precision measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$.
- There are 3× as much data on tape, and the machine is doing better than ever, so there’s more to come.
Backup
Inclusive B x-section

- $\sigma (p\bar{p} \rightarrow H_b)$ from $B \rightarrow D\mu\nu X$ decays.
- Using only 83/pb but systematics-limited.
- Consistent with prev. result using $J/\psi$, and FONLL.

For $p_{T} > 9$ GeV, $|y| < 0.6$:

$\sigma (p\bar{p} \rightarrow H_b) = (1.34 \pm 0.08{\text{ (stat)}}^{+0.13}_{-0.14}{\text{ (sys)}} \pm 0.07{\text{ (BR)}}) \, \mu b \quad \text{(from D}^0\text{)}$

$\sigma (p\bar{p} \rightarrow H_b) = (1.47 \pm 0.18{\text{ (stat)}}^{+0.17}_{-0.19}{\text{ (sys)}} \pm 0.11{\text{ (BR)}}) \, \mu b \quad \text{(from D}^{*+}\text{)}$.

$\sigma (p\bar{p} \rightarrow H_b) = (1.39^{+0.49}_{-0.34}) \, \mu b \quad \text{(FONLL)}$.
excl B+ x-section

\begin{align*}
\sigma (p_t > 6\text{GeV}, |y| < 1) = (2.65 \pm 0.12(\text{stat}) \pm 0.21(\text{sys})) \mu\text{b} \\
\bullet \text{ Measurement/NLO = 2.67\pm0.23} \\
\bullet \text{ Agrees with other } J/\psi\text{-based analyses and FONNL.}
\end{align*}
\[ \frac{d\sigma}{dp_T} (\text{ppbar} \to B)(\text{nb/GeV}) \]

FONLL theory bound

\[ \text{J/}\Psi (1.96 \text{ TeV}) \]
\[ \text{J/}\Psi (1.8 \text{ TeV}) \]

\[ \text{J/}\Psi (1.8 \text{ TeV}) \]
<table>
<thead>
<tr>
<th>$p_T$ range</th>
<th>Central $p_T$</th>
<th>$D^0$</th>
<th>$D^{*+}$</th>
<th>$D^+$</th>
<th>$D_s^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[GeV/c]</td>
<td>[GeV/c]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.5 − 6</td>
<td>5.75</td>
<td>7837 ± 220 ± 884</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6 − 7</td>
<td>6.5</td>
<td>4056 ± 93 ± 441</td>
<td>2421 ± 108 ± 424</td>
<td>1961 ± 69 ± 332</td>
<td>—</td>
</tr>
<tr>
<td>7 − 8</td>
<td>7.5</td>
<td>2052 ± 58 ± 227</td>
<td>1147 ± 48 ± 145</td>
<td>986 ± 28 ± 156</td>
<td>—</td>
</tr>
<tr>
<td>8 − 10</td>
<td>9.0</td>
<td>890 ± 25 ± 107</td>
<td>427 ± 16 ± 54</td>
<td>375 ± 9 ± 62</td>
<td>236 ± 20 ± 67</td>
</tr>
<tr>
<td>10 − 12</td>
<td>11.0</td>
<td>327 ± 15 ± 41</td>
<td>148 ± 8 ± 18</td>
<td>136 ± 4 ± 24</td>
<td>64 ± 9 ± 19</td>
</tr>
<tr>
<td>12 − 20</td>
<td>16.0</td>
<td>39.9 ± 2.3 ± 5.3</td>
<td>23.8 ± 1.3 ± 3.2</td>
<td>19.0 ± 0.6 ± 3.2</td>
<td>9.0 ± 1.2 ± 2.7</td>
</tr>
</tbody>
</table>

TABLE I: Summary of the measured prompt charm meson differential cross sections and their uncertainties at the center of each $p_T$ bin. The first error is statistical and the second systematic.

The products of the branching fractions [11] used are (3.81 ± 0.09)%, (2.57 ± 0.06)%, (9.1 ± 0.6)% and (1.8 ± 0.5)% for $D^0$, $D^{*+}$, $D^+$ and $D_s^+$, respectively.

The total cross sections are obtained by summing over all $p_T$ bins. However, the last $p_T$ bin is replaced by an inclusive bin with $p_T > 12$ GeV/c. We find \( \sigma(D^0, p_T \geq 5.5 \text{ GeV/c}, |y| \leq 1) = 13.3 \pm 0.2 \pm 1.5 \mu b \), \( \sigma(D^{*+}, p_T \geq 6.0 \text{ GeV/c}, |y| \leq 1) = 5.2 \pm 0.1 \pm 0.8 \mu b \), \( \sigma(D^+, p_T \geq 6.0 \text{ GeV/c}, |y| \leq 1) = 4.3 \pm 0.1 \pm 0.7 \mu b \) and \( \sigma(D_s^+, p_T \geq 8.0 \text{ GeV/c}, |y| \leq 1) = 0.75 \pm 0.05 \pm 0.22 \mu b \), where the first uncertainty is statistical and the second systematic. To calculate the
tion are needed to determine whether experimental measure-
mments are consistent with the Standard Model pic-
ture of ... collinear" emis-
sions. As a result, such Monte Carlo programs are often said to
use the " leading-log approximation."
μ-tagged (heavy flavour) jet x-section

- Find jets with muons; estimate heavy flavour content from MC simulation.
- No attempt yet to separate heavy flavour in data (no IP cut or so).
- $\frac{d\sigma}{dp_t}$ generally higher than NLO prediction, but compatible within errors.

**Legend**
- green: $\sigma$(Jet-energy-scale) only
- yellow: all $\sigma$ except $\sigma$(heavy-flavour fraction)
- grey: all systematics
before cosmics veto after cosmics veto

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\( \alpha_{\text{prompt}} \): Prompt J/\psi Polarization

CDF II Preliminary, 800 pb

Polarization from B-decays!

\( \alpha_{\text{B}} \): J/\psi polarizations

zero polarization

error band

w/ 1

B average
Correlated $b\bar{b}$ and $c\bar{c}$ x-section: results

- **x-sections:**
  \[ \sigma_{b\rightarrow \mu, b\rightarrow \mu} = (1549 \pm 133) \text{ pb} \]
  \[ \sigma_{b\bar{b}} (p_T \geq 6 \text{ GeV}, |y| \leq 1) = (1618 \pm 148 \pm [\sim 400 \text{ fragmentation}]) \text{ nb} \]
  \[ \sigma_{c\rightarrow \mu, c\rightarrow \mu} = (624 \pm 104) \text{ pb} \]

- **Ratios (includes both exp. and theory error):**
  \[ \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}} \left( \frac{b\rightarrow \mu, b\rightarrow \mu}{b\rightarrow \mu, \bar{b}\rightarrow \mu} \right) = 1.20 \pm 0.21 \]
  \[ \frac{\sigma_{\text{measured}}}{\sigma_{\text{NLO}}} \left( \frac{c\rightarrow \mu, c\rightarrow \mu}{c\rightarrow \mu, \bar{c}\rightarrow \mu} \right) = 2.71 \pm 0.64 \]

<table>
<thead>
<tr>
<th>Error contributions in % of measured x-section</th>
<th>$b\rightarrow \mu, b\rightarrow \mu$</th>
<th>$c\rightarrow \mu, c\rightarrow \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L , dt$</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>acceptance</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>fake muons</td>
<td>4%</td>
<td>11%</td>
</tr>
<tr>
<td>fit model</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>stat</td>
<td>1.2%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Total</td>
<td>8.6%</td>
<td>17%</td>
</tr>
</tbody>
</table>